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A piezoelectric spring pendulum oscillator used for multi-directional and ultra-low frequency vibration energy harvesting

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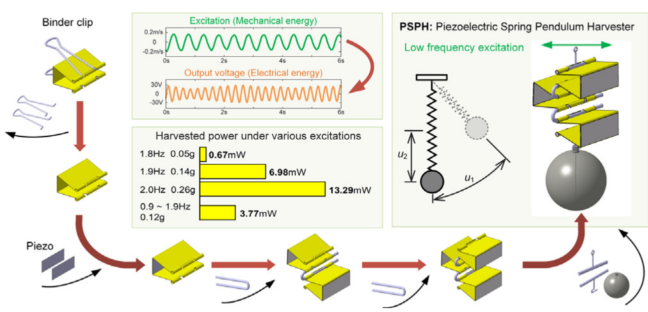
HIGHLIGHTS

- The harvester can scavenge energy from ultra-low frequency vibrations.
- The harvester can capture vibration energy from any direction.
- The harvester can up-convert the excitation frequency through internal resonance.
- The harvester is designed with a novel piezoelectric spring based on binder clips.
- A significant generated power of 13.29 mW (at 0.26 g, 2.03 Hz) is obtained.

GRAPHICAL ABSTRACT



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ABSTRACT

Low frequency vibration is a ubiquitous energy existing in our environment, but a large efficient harvesting of which remains challenging. This paper presents a simple piezoelectric spring architecture based on a common binder clip structure. The harvester with pendulum spring allows the energy of the dynamic mass to be converted into electrical energy in the piezoelectric transducer. Due to the basic characteristics of spring pendulums, the proposed harvester can efficiently scavenge not only ultra-low frequency but also multi-directional vibrational energies. Modeling and design are conducted and a normalized expression of the harvester behavior is given. Chirp and human motion excitations are used to evaluate the proposed harvester's performances. Simulation and experimental results are in good agreement. The proposed device could generate a high output power (13.29 mW) at a low operating frequency (2.03 Hz), which shows great application prospects in the power supply of wearable products, ocean buoys, etc.

1. Introduction

With the fast development of modern science and technology, an increasing number of autonomous devices, such as wireless sensor nodes, Bluetooth bracelets, underwater vehicles, are being widely used in numerous fields. But power supplies are still a critical bottleneck of the above smart devices due to the limited lifetime of batteries and the requirement of regular replacement or recharging, especially when they operate inside bodies, in hostile or dangerous areas, etc. [1]. Thanks to the advanced semiconductor technology, the average power consumption of stand-along devices is usually very low and still keeps on reducing. Energy harvesting form ambient environment to generate sustainable electricity for the mentioned low-power devices is becoming attractive as an alternative to conventional batteries [2]. Solar, thermal, wind and vibration energies are four major examples that we can envisage as possible sources in environment [3]. Though it is difficult to generalize a conclusion that which source is most suitable, vibrational energy transferred by direct piezoelectric effect has drawn great

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attention and has been studied for a decade [4,5]. Moreover, there exists a trend that some researchers prefer to convert thermal [6] or wind [7] energy into vibration energy, and then generate electrical energy through piezoelectric transducers. Though the energy is converted twice, those devices often have better performances for low-power energy harvesting.

In real-world applications, ambient vibrations usually have broadband or time-dependent characteristics in which the energy is distributed over a spread spectrum of frequencies [8]. Resonant-frequency-matching strategy is the classical approach to address the above problem: Developing nonlinear wideband harvesters or developing linear harvester with resonance frequency tuning mechanisms or with multiple vibration modes [9–13]. However, most environmental vibration sources are low frequencies [14,15], e.g., human or animal movements (~ 1 Hz), wave heave motions (< 1 Hz), large construction machinery vibrations (< 10 Hz), and vehicle vibrations (< 20 Hz). In these cases, resonant-frequency-matching strategy would increase the complexity of structure designation: Weak spring and heavy proof mass which leads to large dimensions but flimsy oscillating structure. Another lies in the fact that, the power generation of vibration energy harvester is proportional to the cube of its vibration frequency [16], low frequency means low-power density of the harvester. Consequently, numerous frequency up-conversion (FUC) approaches capable of bridging the gap between high-frequency response and low-frequency excitation have been reported. Generally, FUC approaches can be implemented through five avenues: Mechanical plucking [17,18], mechanical impact [19], impulse-like acceleration [20], impulse-like magnetic force [21,22], and internal resonance [23]. The FUC effect can be touted as the breakthrough to boost the functionality of low-frequency vibration energy harvesters.

Among the above vibration energy harvesters, cantilever-like piezoelectric generators are still the most popular oscillating structures to capture ambient vibration energy [24]. Hence, the solutions proposed are often intrinsically focused on a single incoming direction of vibration. Since practical ambient excitations may come from various directions, multi-directional energy harvesters are presented to maximize the harvested energy. Ando et al. reported a two dimensional nonlinear harvester which simply consisted of two cantilevered beams coupled by magnets to scavenge ambient vibration energy in a wide bandwidth bi-directionally [25]. Chen et al. proposed a dandelion-like piezoelectric generator assembled by many cantilevers and a multi-faceted support body, hence the cantilevered beams were respectively sensitive to vibrate in different directions [26]. Su and Zu presented a piezoelectric harvester consisted of a generating beam and an auxiliary beam, as well as a spring-mass system and three permanent magnets. The harvester could achieve tri-directional sensitivity and broad bandwidth [27]. Recently, Xu and Tang investigated a cantilever-pendulum system, it took the advantage of the nonlinear coupling between the pendulum motion and the beam bending vibration, only one cantilever could effectively transfer the tri-directional excitation energies, greatly enhanced the power density of the harvester [28]. It is worthy of note that the pendular resonant frequency depending on the pendulum length and gravity is usually very low, such cantilever-pendulum device is more suitable for ultra-low frequency vibrations.

Similar to the literature published by Xu and Tang [28], this paper aims at designing, characterizing and testing a piezoelectric spring pendulum harvester (PSPH) which can harvest ultra-low frequency vibration energy in multi-directions. The difference is that the piezoelectric elements are directly integrated with the spring structure instead of a traditional cantilevered beam. Consequently, the strain over the piezoelectric elements is more uniform, the energy harvesting performance is significantly enhanced. An exhaustive analysis of the device with an accurate description of the working principle, numeric modeling, and simulations is presented. An extensive measurement campaign has been performed on an experimental prototype. The results clearly prove that the prototype device has an excellent harvesting performance under ultra-low frequency vibration, which is also a breakthrough for low frequency vibration energy harvesting. In addition, the proposed piezoelectric generator is an inertial-type oscillator and can be completely sealed within a case, this characteristic has great advantages in equipment anticorrosion, maintenance and installation, especially in the field of ocean wave energy harvesting [29,30].

2. Design concept and theoretical model

2.1. Design concept

In the field of piezoelectric vibration energy harvesting, vibrational frequency lower than 5 Hz can be considered as ultra-low frequency vibration. In this case, traditional cantilevered oscillators are usually complicated to be manufactured based on resonant-frequency-matching strategy. Pendulum-like structures are also common mechanical oscillators that could be excited in any direction in the horizontal plane. In addition, their resonant frequencies only depend on the lengths of pendulum l_0 and gravitational acceleration g. Consequently, the resonance of this kind of devices can easily match the ultra-low excitation frequency. However, since the piezoelectric elements are difficult to be integrated with the oscillator, very few literatures have presented such pendulum-like harvesters yet.

In this article, we proposed a PSPH structure (Fig. 1) which consists of a mass, a pendulum spring with bonded piezoelectric elements and an excitation base. The pendulum spring system is based on multiple metal binder clips and assembled by pin structures in series. Its equivalent stiffness is determined by the number of clips. It should be noted that the spring structure can also be once integrally manufactured, provided that the structure parameters have been optimized and the spring has been mass-produced. As can be seen in Fig. 1, one binder clip has 6 faces to handily integrate with 6 piezoelectric ceramics, successfully solve the integration problem mentioned in the last paragraph. Though the integration with more piezoelectric ceramics can achieve the higher electromechanical coupling coefficient, the integration scheme of two pieces of piezoelectric ceramics is selected in this paper, for its maximal conversion efficiency due to the uniform and large strain distributions on the bottom faces.

PSPH, as named, can be simply modeled as a spring pendulum system with the coupled piezoelectric elements. Dynamic behavior of such nonlinear spring pendulum system has attracted numerous interests of researchers [31,32]. In a strict sense, any directional vibration energy in three-dimensional space may excite the PSPH and be converted into electrical energy. We assume that the original length of the assembled spring is l_0, this value is the minimum length of the spring and cannot be compressed. Fortunately, the proposed structure is a

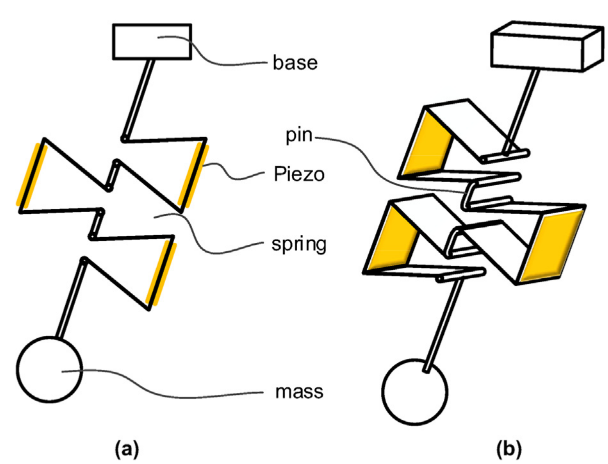

Fig. 1. Piezoelectric spring pendulum energy harvesting structure: (a) side view; (b) three-dimensional view.